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LUNAR ENTRY DOWNMODE OPTIONS FOR ORION

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For Exploration Missions 1 and 2, the Orion capsules will be entering the Earth's atmosphere with speeds in excess of 11 km/s. In the event of a degraded Guidance, Navigation, and Control system, attempting the nominal guided entry may be inadvisable due to the potential for failures that result in a loss of vehicle (or crew, when crew are aboard). In such a case, a method of assuring Earth capture, water landing, and observance of trajectory constraints (heating, loads) is desired. Such a method should also be robust to large state uncertainty and variations in entry interface states. This document will explore four approaches evaluated and their performance in ensuring a safe return of the Orion capsule in the event of onboard system degradation.

INTRODUCTION

In late 2018, NASA is planning to launch an un-crewed Orion vehicle atop the Space Launch System on a mission to the Moon. Orion is expected to orbit the Moon in a distant retrograde orbit, hereafter referred to as the DRO. The vehicle will loiter near the Moon in the DRO for approximately 14 days prior to returning to Earth. Once the returning Orion encounters the highest reaches of the sensible atmosphere (defined at 400,000 ft altitude), it will be traveling in excess of 11,000 meters per second. In the nominal mission design, Orion will perform a guided entry that will result in a water landing off the coast of Southern California for recovery. Guided entry is performed by banking in the atmosphere to control the magnitude of the upward component of aerodynamic lift. By modulating its bank angle, Orion is able to control its downrange and crossrange flown from entry interface until splashdown to achieve precision-landing.

There exist certain failure modes on Orion in which attempting a guided entry is inadvisable. For instance, if a propellant leak has occurred in one of the two isolatable fuel tanks onboard Orion (rendering half its loaded propellant unavailable), the vehicle must conserve its propellant during hypersonic entry so that sufficient propellant is available for sub-sonic stabilization and for controlling touchdown orientation at splashdown. The nominal integrated guidance-control system does not make efforts to actively constrain propellant usage during hypersonic entry. As a result, with only half of the propellant available, there may not be sufficient fuel to perform all tasks with the required reliability. Another potential failure mode identified is failure to acquire GPS measurements once the vehicle descends below the GPS constellation service envelope. In this case, Orion's onboard estimate of its state will be less accurate, and these navigation errors will result in degraded guided entry performance. With large enough navigation errors, large guidance misses at the landing site will result. At sufficiently high speeds and with sufficiently large onboard state estimation

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errors, the vehicle could inadvertently land on landmass posing a potential risk to populated areas in addition to the potential for its own structural failure upon impact with terrain.

Originally designed as a contingency entry mode when Orion was being designed to return crews from the International Space Station, a ballistic entry mode is available to Orion. When performing a ballistic entry, Orion will spin itself clockwise about its longitudinal axis until it achieves a $+15^\circ/\text{s}$ bank angle rate. The intent is to spread the aerodynamic lift in all directions equally in time with the intent of nulling the integrated effects of lift. All that is required to perform a ballistic entry is an attitude control system capable of inducing a roll rate and knowledge of the current attitude rate (derived from IMUs).

As long as the vehicle failure is known prior to entry interface, the ground or crew can command the vehicle to initiate the ballistic spin upon atmosphere entry and reliably capture, assuming the EI state is within the set of acceptable EI states. In this case, landing accuracy is sacrificed for survival. Generally, ballistic entry can be considered to be a type of uncontrolled entry, and as such tends to incur higher levels of deceleration than lifting, controlled entries.

EXTENSIBILITY TO LUNAR RETURN SPEEDS

Although the velocity at Entry Interface is typically $\approx 40\%$ larger for a lunar return than a typical low Earth orbit (LEO) return, the kinetic energy is nearly double! In other words, to ensure safe capture, significantly more energy must be safely depleted before capture can occur.

However, a ballistic entry may begin during atmospheric entry flight if all primary flight computers fail simultaneously (due to a common-cause software error) and the vehicle hands control to a dynamic Backup Flight Software, a dissimilar set of flight control algorithms. If a ballistic entry abort is initiated, the current baseline is to initiate a clockwise rotation (positive) bank rate. However, this strategy is susceptible to failure in certain scenarios. The vehicle may end up skipping out of the atmosphere or overflying the landing site (potentially landing on land). This tends to occur when the vehicle transitions to the ballistic spin logic while a previously commanded bank reversal slew maneuver is underway.

In this scenario, the vehicle's guidance algorithm has commanded a bank angle reversal just prior to the unplanned handover to the backup flight software. In this case, the vehicle may either rotate clockwise or counter-clockwise, depending on whichever rotation direction results in a shorter time to reach the commanded bank angle.

If ballistic entry is initiated in the middle of a counter-clockwise bank reversal maneuver, the vehicle must first arrest its counter-clockwise rotation rate (de-spin), and then continue its spin maneuver until it achieves its desired clockwise bank rate. During this de-spin and spin-up maneuver, the vehicle's lift vector may be directed mostly upwards over an extended period of time (15+ seconds) during this transient. If this "mostly-lift-up" interval coincides with peak dynamic pressure (and control authority), then the vehicle could inadvertently skip-out of the atmosphere or overfly the target (an undesirable result!).

To illustrate the magnitude of the problem, consider the success rates for ballistic aborts initiated mid-flight, where success is defined as a trajectory that does not skipout $h_{max} > h_{EI}$ and does not overfly its landing target (potentially resulting in land landings). The plot below shows the success rates for ballistic aborts initiated some time after entry interface, where "success" is defined by the

logical condition in Equation 1.

$$Success = (h_{max} \leq h_{EI}) \wedge (\neg FlewPast) \quad (1)$$

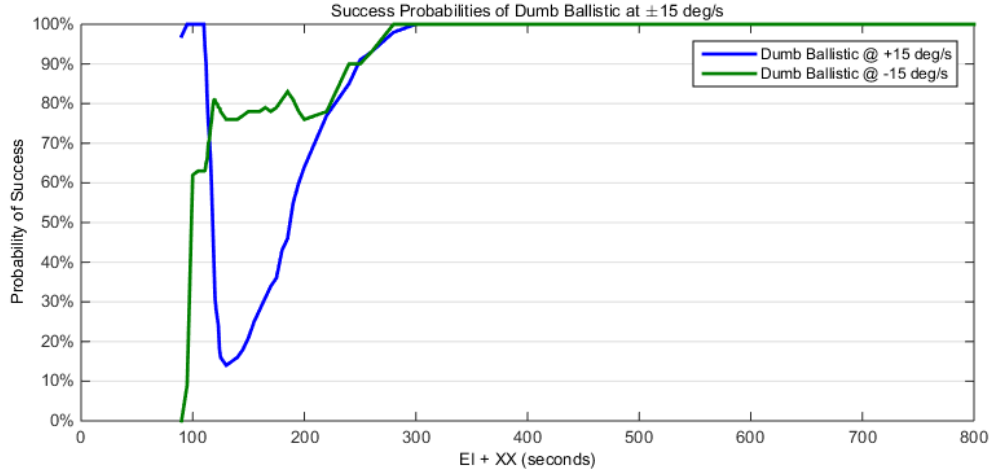


Figure 1. Comparison of success between clockwise and counter-clockwise ballistic entries initiated at different times after entry interface

As shown in Figure 1, the baseline ballistic experiences over an 80% failure rate for ballistic entries initiated in the interval of EI+125 seconds to EI+150 seconds. This interval corresponds to the typical timing of the first counter-clockwise bank reversal and simultaneous pull-out maneuver as flown by a healthy entry guidance system. This interval could be considered to be a “black zone” where in-flight ballistic aborts should be avoided.

To maximize crew safety and safe abort coverage, continuous in-flight ballistic entry abort capability is required by Orion for crewed flights. This problem of ballistic skip-out must be resolved prior to crewed flights.

MITIGATIONS

From a better understanding of the causes of the problem, a mitigation strategy may be developed that directly attacks the root cause. Simply put, the vehicle spends too much time applying lift upward (or not sufficiently downward) during this critical interval. The solution requires that the lift be sufficiently directed downward such that atmospheric capture is assured.

Smart Ballistic

Recall that the current ballistic scheme always executes a clockwise (positive) bank rate, regardless of the current state of the vehicle. While staying within the constant spin-rate framework, a slightly more intelligent approach would be to consider the effects of the integrated lift if the vehicle were to perform a clockwise (positive) or counter-clockwise (negative) spin rate. However, such a direct method would require numerical integration of the equations of motion for a lifting spacecraft. However, this software complexity is unappealing for an emergency backup system. Instead, a simpler solution is desired that attempts to capture all the benefits of a complex, direct methodology.

To this end, a simpler scheme has been developed. Instead of numerically modeling the equations of motion during the spin-up maneuver and ballistic spinning flight, it may be sufficient to simply evaluate the time required for the vehicle to achieve the targeted condition of bank= 180° and bankRate = $+15^\circ/\text{s}$. If the time to achieve these terminal conditions was compared for a clockwise spin against a counter-clockwise spin ($-15^\circ/\text{s}$), then the logic could select the direction that minimizes the time to reach this terminal state. The underpinning idea is that by selecting the spin rate direction that minimizes the time to full lift down, we simultaneously minimize the amount of lift directed upwards over the time interval where ballistic spin-up occurs.

This approach of selecting the spin direction that minimizes the time to the terminal conditions is hereafter referred to as *Smart Ballistic* to distinguish it from the the current baseline, which could be characterized as un-informed, reactive, or more simply as “dumb.”

The performance comparison of the the so-called Smart Ballistic against the baseline dumb ballistic is shown in Figure 2.

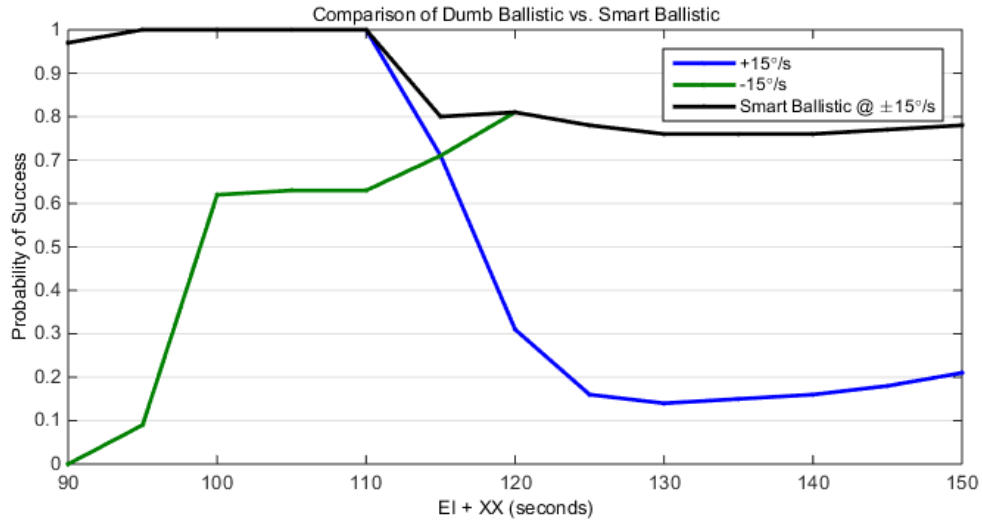


Figure 2. Comparison of Smart Ballistic with Dumb Ballistic

Figure 2 shows that Smart Ballistic matches the best performance of either constant-spin direction strategy and exceeds the performance during the interval of EI+110 seconds to EI+120 seconds. In that interval, Smart Ballistic is choosing the “best” spin direction, and thus it can have the best of either worlds. However, after EI+115 seconds, there stubbornly remains at least a 20% failure rate even when performing a Smart Ballistic maneuver.

Investigation of these failures led to further insights which led to the subsequent approaches detailed in the subsequent sections.

To summarize, the Smart Ballistic algorithm always outperforms the Dumb Ballistic algorithm across the scenarios analyzed, but this approach has not eliminated the problem of ballistic skip-out.

Effects of Ballistic Spin Rate

While Smart Ballistic increases the probability of success, it may be possible to further increase the probability of success by adjusting the targeted ballistic spin rate magnitude.

Recall that the philosophy behind a ballistic spin is to approximately apply the aerodynamic lift in all directions normal to the direction of travel such that the effective integrated lift is approximately null. As such, the only two forces acting upon the vehicle are aerodynamic drag (resisting motion) and gravity; as such, the object's motion could be characterized using a non-lifting ballistic analysis.

With this philosophy, a slower ballistic spin rate would tend to less effectively null the integrated lift, and a faster spin rate would tend to better smear the lift over different directions in time, thus more effectively nulling the integrated lift.

However, implicit in this thought experiment is that the magnitude of the lift is sufficiently constant over time, such that the lift force applied at some t_0 applied some bank θ_0 is approximately equal at some later time $t_0 + \Delta t$ when $\theta_0 + \pi$.

However, the magnitude of the lift force dramatically varies in time during the first entry as the vehicle dips into and climbs out of the atmosphere. Generally, the vehicle experiences little drag during its initial plunge into the atmosphere while density is still low, and then suddenly the vehicle collides headlong into a wall of aerodynamic resistance. This sudden onset of acceleration shall be referred to as the G-spike in this paper. Just as quickly as it comes, the aerodynamic resistance will taper off into nothingness as the vehicle climbs higher into more rarefied air.

If the time when the lift vector happens to be directed primarily upwards is coincident with the timing of the G-spike, then it is significantly more likely for a skip-out to occur. Directing lift upwards increases the flight path angle, and when integrated over time, it results in the vehicle remaining higher in the atmosphere where the atmosphere is less dense. In flight regimes with less atmospheric density, the aerodynamic drag decreases, thus depleting less energy from the vehicle. This results in the vehicle flying faster for a longer period of time, which in turn results in longer ranges flown or even atmospheric skip-out.

Thus, it is possible that poor timing in initiating a ballistic spin could result in a skip-out if the resulting spinning bank profile is adversely coincident with the G-spike; in other words, its lift vector is not directed sufficiently downwards *over the right time interval* to cause the vehicle to capture in the atmosphere.

In order to improve performance (reducing probability of skip-out), the targeted ballistic spin rate magnitude was increased in the simulation (to $\pm 20^\circ/s$) with the intent to reduce the amount of time spent directing lift upwards. Surprisingly, the vehicle skipped out even more frequently than $\pm 15^\circ/s$, an unexpected result! After some analysis, the root cause was determined: the vehicle simply spent too little time directing lift downward during the interval of peak control authority.

What was happening was that the vehicle was acting too much like an idealized ballistic body at higher spin rates and did not direct enough lift downwards during its G-spike.

Thus, spinning more quickly was a double-edged sword: it decreased the time spent lift up (tends to produce skip-out), but it also decreased the time spent lift down (tends to produce capture).

Next, the spin rate magnitude was decreased from $\pm 15^\circ/s$ to $\pm 10^\circ/s$, performance improved by allowing the vehicle to steepen its trajectory and deplete more energy. When the spin rate was further decreased to $\pm 5^\circ/s$, performance improved beyond the $\pm 10^\circ/s$ scheme!

If the vehicle is enabled to pursue a "slow & smart spin" strategy at $\pm 5^\circ/s$, it significantly outperformed the other spin-rate options. This is because the "slow" spin strategy allows the vehicle to apply the lift downward at the right time for a sufficient duration, coincident with the G-spike, to allow it to deplete enough energy to capture in the atmosphere and not overfly the target.

Figure 3 shows how the probability of success changes with decreasing spin rates.

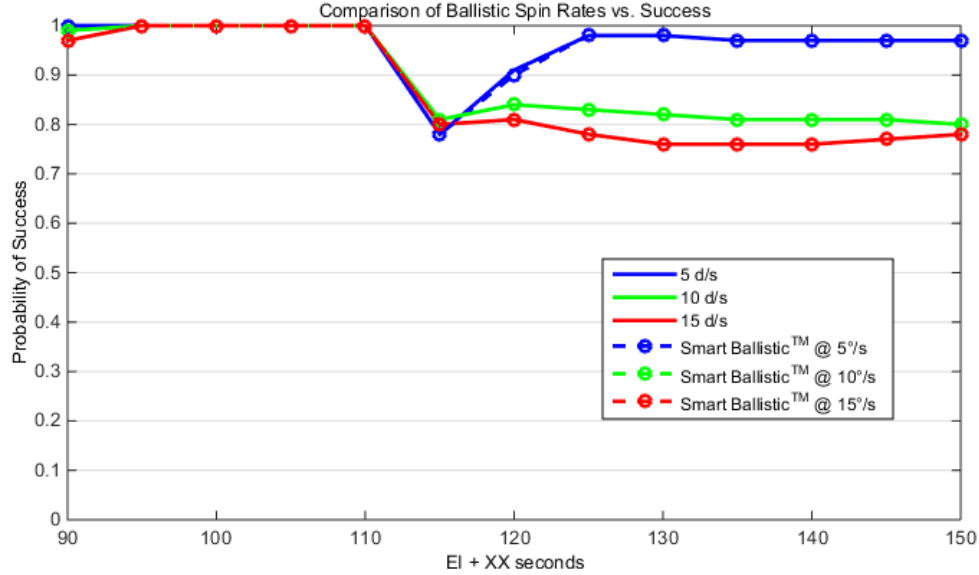


Figure 3. Comparison of Varying Spin Rate with Smart Ballistic

Clutch Algorithm

Even with the improvements described above, the "slow & smart spin" strategy had still not, frustratingly, eliminated the problem of ballistic skip-out in all cases. Confined to the constant-bank-rate paradigm, the vehicle's spin rate would have to be slowed further in hopes that it could stay directed lift downwards even longer. However, this also necessarily implies that the vehicle will maneuver slowly toward full-lift down and spend significant time directing lift upwards if starting in a disadvantageous attitude state.

Throwing off the shackles of the constant-bank-rate paradigm, a different method was considered.

A potential different approach for avoiding the skip-out problem for an emergency entry is to simply fly full-lift down (bank= 180°) until target overflight is impossible (and thus preventing atmospheric skip-out); after this condition is achieved, then the vehicle is free to fly any other bank angle. The vehicle could then fly with a $\sigma = 0^\circ$ (full-lift up) attitude to minimize peak deceleration loads and associated aeroheating. There is no attempt to minimize miss distance relative to a landing site; rather, the intent is entirely to assure atmospheric capture and survival.

The key for this method's success is to define a simple "capture" indicator which can be computed reliably even in the presence of large state estimate errors. A promising solution for this "capture" indicator is inspired by the simplified problem of ballistic vehicle targeting from Ref.¹ Considering

only in-plane motion, an ascent vehicle must terminate its powered boost phase at some position, velocity, and flight path angle. When those three parameters are known, the subtended arc (while in free-flight) can be calculated with simple orbital mechanics.

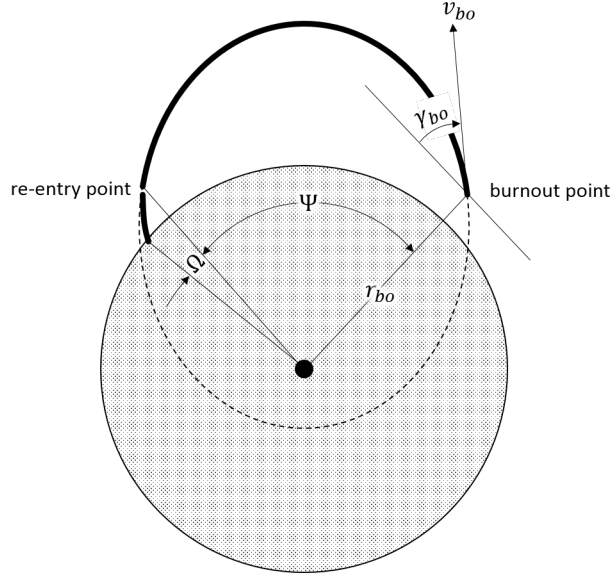


Figure 4. Illustration of ballistic free-flight following burnout at initial conditions $(r_{bo}, v_{bo}, \gamma_{bo})$ as depicted in¹

From,¹ the solution is presented after a brief derivation:

$$\sin \left(2\gamma_{bo} + \frac{\Psi}{2} \right) = \frac{2 - Q_{bo}}{Q_{bo}} \sin \left(\frac{\Psi}{2} \right) \quad (2)$$

where

$$Q_{bo} = \frac{v_{bo}^2 r_{bo}}{\mu} \quad (3)$$

where γ_{bo} = Burn-out Inertial Topocentric Flight Path Angle,

Ψ = Range Angle to Target,

Q_{bo} = Square of Ratio of inertial velocity to circular satellite velocity at burnout,

v_{bo} = Inertial velocity magnitude at burnout,

r_{bo} = Position radius magnitude at burnout,

μ = Gravitational parameter GM

When $Q > 2$, the conic is hyperbolic; $Q = 2$, the conic is parabolic; $Q = 1$, the conic is circular. For reference, the vehicle's energy on lunar return trajectories is nearly parabolic ($Q \approx 1.99$).

We can apply this relationship to help our vehicle ensure capture at Earth if we set Ψ equal to the subtended angle between the current position vector and the landing site vector. The vehicle should

deplete energy in the atmosphere through drag until its flight path angle γ is less than the critical ballistic flight path angle γ_{bo} , as determined based on the current state (r, v) and range-to-go Ψ . With those variables known, the expression can be solved for the critical flight path angle γ_{bo} .

The vehicle can apply its lift downward (nadir) to steepen its flight path angle γ to match the critical flight path angle γ_{bo} . At that point, if the atmosphere (and its aerodynamic effects) instantaneously disappeared, the vehicle would fly a ballistic (gravity only) arc that terminates at the landing site at the current altitude. This is equivalent to flying lift down until the distance from the current position to the vacuum instantaneous impact point (VIIP) is less than or equal to the current range to the landing target.

However, there is an atmosphere, and the atmosphere will continuously deplete energy from the vehicle through aerodynamic drag (non-conservative force). As a result, the non-conservative forces applied over the remaining trajectory will necessarily shorten the ultimate range flown.

This is a sufficient condition to guarantee landing short of the landing site as long as the vehicle behaves sufficiently "ballistically" over the coasting arc. Because the vehicle is non-thrusting and mechanical energy cannot be increased, vehicle energy can only be depleted as the trajectory proceeds via non-conservative forces (atmospheric drag). Furthermore, because this critical flight path angle γ_{bo} does not account for energy depletion through drag, it will never under-estimate (always either over-estimates or precisely estimates) the predicted range that will be flown from a given state, assuming the vehicle behaves sufficiently ballistically (non-lifting).

Re-arranging the expression above, we can solve directly for the γ_{bo} :

$$\gamma_{bo} = \frac{1}{2} \left[\sin^{-1} \left(\frac{2 - Q_{bo}}{Q_{bo}} \sin(\Psi/2) \right) - \Psi/2 \right] \quad (4)$$

Note that the above function has two valid solutions which correspond to the low arc solution and high arc solution. For this particular application, we only care about the lower arc solution. In this algorithm, this critical flight path angle γ_{bo} is compared against the current flight path angle γ . If $\gamma > \gamma_{bo}$, then the vehicle is predicted to overfly its landing site in a vacuum (no drag). Once $\gamma \leq \gamma_{bo}$, then it is guaranteed that a ballistic object cannot overfly its target (in a vacuum).

A simple switching logic can be employed to switch the bank command σ from $\sigma=180^\circ$ to $\sigma=0^\circ$ such as:

$$\sigma_{capture} = \begin{cases} 0, & \gamma \leq \gamma_{bo} \\ \pi, & \gamma > \gamma_{bo} \end{cases} \quad (5)$$

The above algorithm will capture in minimum time, because the saturated value of $\sigma = 180^\circ$ maximizes the downward acceleration where the largest energy depletion occurs. However, there is no requirement that the vehicle achieve capture in minimum time. In fact, such a strategy will suffer from excessive peak deceleration loads.

In initial testing, the conservative estimate for downrange to-be-flown resulted in dramatic behavior which subjected the vehicle to catastrophic peak deceleration loads in excess of 35g's when flying with the bang-bang switching logic described earlier ($\sigma=180^\circ$ or $\sigma=0^\circ$). These G-loads could be reduced by tuning the "downward" bank angle, but a more automated solution was desired to minimize long-term maintenance of the algorithm over the life of the vehicle.

To address this problem, the load relief technique from² was appended to the analytic vacuum downrange prediction algorithm. At a high level, the load relief algorithm from² works by predicting (via several first order approximations) the drag acceleration that will be experienced at some future time $t + \Delta t$. Then, if the predicted drag acceleration exceeds the peak deceleration constraint, then the bank angle is adjusted to shallow the flight path angle γ enough to satisfy the peak deceleration constraint $a \leq a_{max}$. Because of its predictive nature, it helps to anticipate and lessen deceleration spikes during entry flight.

$$\sin(\gamma_G) \geq \frac{g_{max} - a(1 - 2D\delta/V_\infty)}{aV_\infty \left(\frac{-1}{H_S}\right) \delta} \quad (6)$$

where γ_G = G-Load Constrained Inertial Topocentric Flight Path Angle,

g_{max} = Peak deceleration acceleration,

a = Sensed acceleration magnitude,

D = Sensed drag acceleration,

δ = Time horizon of first order deceleration prediction,

V_∞ = Atmospheric-relative velocity magnitude,

H_S = Exponential atmospheric density scale height

$$\sin \gamma_{ref} = \begin{cases} \sin \gamma_G, & \gamma_G > \gamma \\ \sin \gamma, & \gamma_G \leq \gamma \end{cases} \quad (7)$$

$$\cos(\sigma_{cmd}) = f(a, \dot{h}, V_\infty) = \cos(\sigma_{capture}) - \frac{k_{\dot{h}}}{a \cos\left(\tan\left(\frac{L}{D}\right)\right)} (\dot{h} - V_\infty \sin \gamma_{ref})$$

where $k_{\dot{h}}$ = Altitude Rate Error Controller Gain

$\frac{L}{D}$ = Lift to Drag ratio

σ_{cmd} = Final G-constrained bank angle command

When these two algorithms are tied together in sequence (vacuum downrange estimate and load relief), the combined algorithm works well to assure capture and maintain relatively low deceleration loads. In effect, the load relief algorithm helps to moderate the raw bang-bang command generated by the vacuum downrange estimation algorithm.

In pseudo-code, the simplified algorithm may be written as

```
function bankCMD = clutch(accelMag, hDot, vMag, Psi, LoD)
% Inputs:
% accelMag = magnitude of sensed acceleration
% hDot = altitude rate
% vMag = magnitude of inertial velocity vector
% Psi = range angle to target
% LoD = lift-to-drag ratio
```

```

k_hDot = 100; % Gain for altitude rate controller
maxG = 10; % 10-g limit for crewed vehicle
delta = 16; % time horizon for load relief algorithm [seconds]
scaleHeight = 8686.8; % Atmospheric scale height for simplified
    exponential density model [ meters ]

% Computed parameters
aoa = tan(LoD); % Angle of attack is tangent of lift-to-drag ratio.
drag = cos(aoa)*accelMag; % Drag acceleration
lift = sin(aoa)*accelMag; % Lift acceleration
fpa = asin(hDot / vMag); % Flight path angle
Q_bo = velMag*velMag*r / mu; % Squared ratio of inertial velocity to
    circular satellite velocity

% ---- Algorithm ----
% Compute burnout flight path angle that flies the range angle from the
    given position & velocity.
fpa_bo = 0.5*(asin( ((2-Q_bo)/Q_bo)*sin(Psi*0.5)) - Psi*0.5);

% Set value of cos(bank) for the capture bank angle (capture stage)
cosBankCapture = 1*(fpa <= fpa_bo) - 1*(fpa > fpa_bo);

% Compute g-load constrained flight path angle
fpa_constrained = (maxG - accelMag*(1-2*drag*delta/vMag) /
    (accelMag*vMag*(-1/scaleHeight)*delta);

% Convert flight path angle into altitude rate
hDot_constrained =vMag * max(fpa, fpa_constrained);

% Compute g-load constrained bank angle (load relief stage)
cosBankClutch = cosBankCapture - (k_hDot / lift) * (hDot -
    hDot_constrained);

bankCMD = acos(cosBankClutch);

end

```

The performance of the Clutch algorithm as compared to the other proposed approaches is shown in Figure 5.

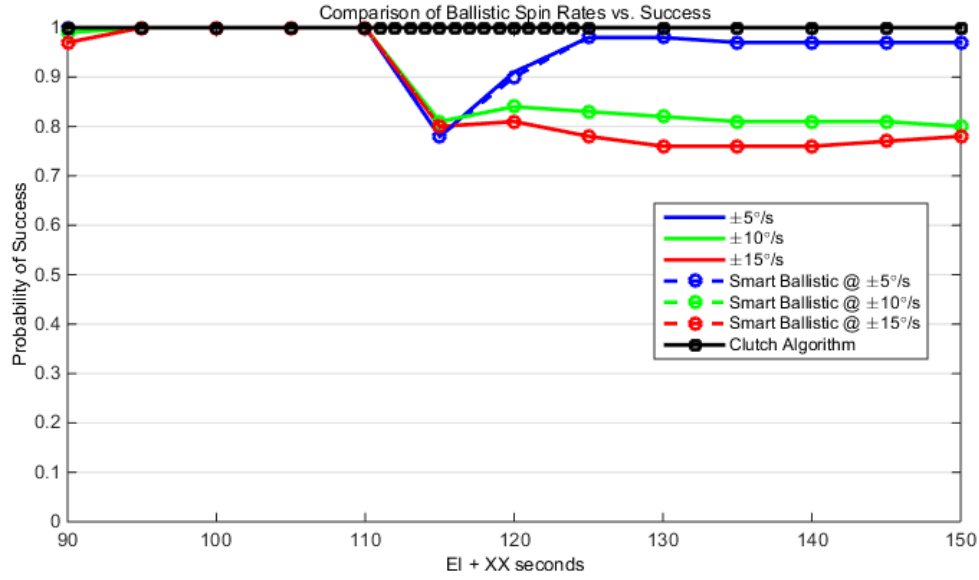


Figure 5. Comparison of Clutch with Smart Ballistic at varying spin rates

As shown in Figure 5, Clutch entirely eliminates the problem of ballistic skip-out since it works to inhibit target overflight (thus assuring capture) while avoiding catastrophic deceleration loads.

The combined two-stage algorithm is conceptually simple and computationally inexpensive, requiring no iteration. This makes it appealing as an option for Orion's backup flight software system for emergency entry. Additionally, the vacuum downrange predictor is robust to large navigation errors. The load relief algorithm is more sensitive to navigation errors, and this sensitivity will motivate future analysis to increase its robustness. One downside of the Clutch algorithm is that it requires additional state information (r, v, γ, a, Ψ) beyond the baseline ballistic algorithm or Smart Ballistic algorithm.

With the more effective capture performance for emergency downmodes, an initial study has demonstrated that the current operational entry corridor may be expanded to include shallower flight path angles without accepting more risk of skip-out. The existing active constraint on the shallow side of the corridor (in flight path angle) is the ballistic lofting constraint. Expanding the operational entry corridor has wide-ranging ripple effects throughout the entire vehicle design, including navigation (onboard and ground) accuracy, burn execution errors, heatshield mass, etc.

The reason landing short of the target is valuable is because the EI states selected for lunar returns already account for near-continuous water beneath the entry groundtrack for purposes of disposing the service module. As such, the vehicle is assured of a water landing for a ballistic entry abort with this proposed approach.

SUMMARY

A set of improvements to the current ballistic abort mode were evaluated to quantify their effectiveness in preventing atmospheric skip-out and target overflight. Smart Ballistic outperformed Dumb Ballistic (baseline). Smart Ballistic with an slower spin rate outperformed Smart Ballistic

at $\pm 15^\circ/\text{s}$. Finally, the Clutch eschewed from the constant spin rate approach and entirely eliminated the ballistic skip-out problem, dominating all other options considered. The Clutch algorithm will be considered as a candidate approach as an intermediate entry downmode option for Orion's crewed Exploration Mission 2.

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- [1] R. R. Bate, D. D. Mueller, and J. E. White, *Fundamentals of Astrodynamics*. New York: Dover Publications, 1971.
- [2] P. Lu, "Entry Guidance: A Unified Method," *Journal of Guidance, Control, and Dynamics*, Vol. 37, No. 3, 2014, pp. 713–728.